Global Food Security 17 (2018) 154–161

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Food waste for livestock feeding: Feasibility, safety, and sustainability implications

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ARTICLE INFO

Keywords:
Food waste
Sustainability
Climate footprint
Waste management
Animal feeding
Food security

ABSTRACT

Food waste is a matter intrinsically linked with the growing challenges of food security, resource and environmental sustainability, and climate change. In developed economies, the largest food waste stream occurs in the consumption stage at the end of the food chain. Current approaches for dealing with the wasted food have serious limitations. Historically, livestock animals had functioned as bio-processors, turning human-inedible or -undesirable food materials into meat, eggs, and milk. Contemporary treatment technologies can help convert the food waste into safe, nutritious, and value-added feed products. Recovering consumption-stage food waste for animal feeding is a viable solution that simultaneously addresses the issues of waste management, food security, resource conservation, and pollution and climate-change mitigation.

1. Introduction

Food waste is a matter intrinsically linked to food security. Globally, an estimated 1.3 billion tons of food for humans is lost and wasted each year (Gustavsson et al., 2011), enough to feed more than one billion people. Food waste is also a resource and sustainability issue. The processes of food production consume vast resources of land, water, energy, fertilizer and other inputs, meanwhile engendering environmental adversities, e.g. biodiversity and habitat loss, soil and water degradation, and greenhouse gas emissions. With food being wasted, the resources and environmental impacts are sacrificed in vain. To sustainably meet the growing food demand amid climate change and dwindling resources, enhancing the utilization of food produced and cutting down waste is a necessity (e.g. Foley et al., 2011).

Food waste occurs at every stage of the food system from farm to fork (Xue et al., 2017). In developed countries, the largest waste stream is generated at the end of the food chain, including consumer-facing businesses (supermarkets, grocery stores, distribution centers; restaurants; institutional food services) and homes. For example, estimates of annual food waste in the U.S. food system amount to 9.1, 0.9, and 47.2 million tons (Mt) on farms, in manufacturing industries, and at the consumption stage in the end, respectively (ReFED, 2016). The latter consists of 22.7 Mt in consumer-facing businesses and 24.5 Mt in homes (together referred to as consumption-stage food waste hereafter). Currently, consumption-stage food waste is largely destined to landfills in many developed economies. For example, roughly 3/4 of food waste in the U.S. ends up in landfills according to a U.S. EPA estimate (2016). There are growing efforts worldwide to lessen landfill burdens, with alternative options currently promoted including composting, anaerobic digestion, incineration, or feeding to livestock animals (Kim et al., 2011; U.S. EPA, 2016). Notably, none of the options directly address sustainable food security challenges, except for livestock feeding.

Recovering food waste for animal feeding (ReFeed) is a viable option that has the potential to simultaneously address waste management (landfilling), food security, and resource and environmental challenges. Livestock animals function as bio-processors for converting food materials that are either unpalatable/inedible or no-longer-wanted by humans into meat, eggs, and milk. This would concomitantly 'spare' feed grains and relevant resources and environmental burdens associated with the production of the feed grains. Historically, feeding food waste and food production residuals to livestock animals has long been practiced in many parts of the world (Westendorf, 2000). However, the age-old practice lost its popularity with the advent of intensive animal feeding operations, which now operate with precision feeding using feed grains such as maize and soybeans for maximum productivity (Banhazi et al., 2012). Today, as the society strives to sustainably feed

Abbreviations: FDF, feeds derived from food waste; ReFeed, recovering food waste for animal feeding

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https://doi.org/10.1016/j.gfs.2017.12.003
Received 17 November 2017; Received in revised form 7 December 2017; Accepted 9 December 2017

the growing population while mitigating environmental damages, there is a renewed interest in reinvigorating the practice (e.g. Stuart, 2009). For example, food waste repurposing to animal feed is identified as one of the food waste recycling solutions in the U.S. (ReFED, 2016). In Europe, "re-legalization" of the use of food waste for pigs could reduce the cropland associated with European pork production by 1.8 million ha (zu Ermgassen et al., 2016b). Also, the FAO recently sponsored an e-conference to promote food waste treatment technologies and encourage government support and public outreach (Thieme and Makkar, 2016).

To evaluate ReFeed as a national and global strategy for simultaneously addressing sustainable food security as well as waste management challenges, a comprehensive analysis with science- and field-based evidence demonstrating the feasibility, safety, and sustainability implications is needed. The objective of this article is to perform such an analysis while identifying existing data gaps. The article first examines the nutritive attributes of food waste, animal performance in feeding trials, and methods of food waste treatment for feeding (Section 2). Next, a synthesis of relevant resource and environmental implications is provided (Section 3), followed by discussion of potential health/safety issues as well as case studies from selected countries (Section 4). Section 5 explores potential concerns and ways to address them. Finally, concluding remarks are presented in Section 6.

2. Feasibility

2.1. Overview and boundaries

Recently-published work on feeding food waste to livestock animals mostly originates from South Korea, Japan, Taiwan, India, and South American countries. Pig feeding dominates those studies, although other animal species have been tested as well, including poultry (Chen et al., 2007), beef and dairy cattle (Angulo et al., 2012; Paek et al., 2005), and small ruminants (Summers et al., 1980).

A variety of food waste materials, varying in source and type, have been used in feeding studies. These food wastes can be categorized into three major types: (i) manufacturing co-products/ byproducts, with typically uniform and known ingredients, e.g. wheat middlings, oilseed meals, etc., (ii) food preparation or processing refusals/residuals, such as those from large-scale bakeries or produce processing/packing facilities, (iii) a hodgepodge of wasted food from food service places (e.g. restaurants, cafeterias) or homes, with the content unpredictable. This article focuses on studies using the consumption-stage food waste for animal feeding. This is because manufacturing co-products/byproducts and food-processing refusals/residuals are already routinely used in animal feeding. For instance, in the United States, 10.9 Mt milling co-products, 30.4 Mt oilseed meals, and 2.5 Mt animal proteins, plus an estimated 27 Mt brewing and ethanol co-products are fed to livestock animals on an annual basis (Ferguson, 2016). This feeding practice is favored by economies of scale and predictability of quantity and quality of the byproduct materials. In fact, manufacturing byproducts are not included in the food waste estimates in the U.S. (ReFED, 2016). On the other hand, consumption-stage food waste, being the largest waste stream generated in the food chain, presents the greatest challenge. Its recovery and treatment for animal feeding has a tremendous significance, given its magnitude and the limitations of other management options.

2.2. Nutritive attributes of food waste

Results pooled from 23 trials (summarized in Table 1) in the literature had the means and coefficients of variation for major nutrition parameters in consumption-stage food waste samples as: dry matter 21.7% (CV 25.0%), crude protein 19.2% (24.5%), crude fiber 6.2%

Table 1
Major nutritional parameters of food waste samples for the purpose of livestock animal feeding, as reported in the literature.

Reference	Sample type	*n*	DM%		CP%		EE%		NFE%		Fiber%		Ca:P
			Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean
Chen et al. (2007)	DFW	5	87.6	2.4	15.8	3.4	16.0	3.2	–	–	10.8	11.1	1.51
Chen et al. (2015)	Method 1	60	20.2	37.6	25.5	34.9	28.1	25.3	31.6	19.6	7.3	46.6	–
	Method 2	60	19.4	43.8	28.3	32.5	25.3	31.2	23.0	40.9	6.9	52.2	–
	Method 3	60	18.8	21.8	30.6	25.3	31.5	26.0	28.6	27.6	3.0	63.3	–
García et al. (2005)	Restaurant	28	39.6	18.7	27.5	23.3	28.8	29.5	26.9	49.1	2.3	47.8	–
	Household	34	33.1	32.6	16.3	29.4	11.3	35.4	41.8	33.5	12.4	62.1	–
Jin et al. (2012)	Restaurant	6	22.8	5.4	28.6	11.9	31.5	6.7	–	–	3.1	61.3	–
Kornegay et al. (1965)	Restaurant	30	16.0	28.3	15.3	24.1	24.9	33.0	50.7	18.3	3.3	42.6	–
	Institutional 1	28	13.7	23.7	13.9	23.2	11.6	57.0	67.4	10.6	2.8	53.1	–
	Institutional 2	30	21.4	11.3	15.3	14.1	17.8	27.5	57.8	11.1	2.8	28.9	–
	Military 1	28	27.5	24.1	15.6	22.5	34.0	31.3	41.9	16.8	2.9	48.3	–
	Military 2	28	23.8	11.7	16.3	21.3	30.0	24.8	45.7	16.7	2.7	23.7	–
	MSW	21	16.6	46.3	17.5	26.2	21.4	33.9	44.0	24.3	8.4	54.1	–
Kwak and Kang (2006)	Restaurant	–	19.1	–	22.0	–	23.9	–	33.9	–	7.6	–	–
Murray Martínez et al. (2012)	Restaurant	5	24.3	–	5.6	–	9.3	–	8.2	–	0.6	–	–
Myer et al. (1999)	Trial 1	–	11.4	–	15.0	–	13.8	–	–	–	10.3	–	1.59
	Trial 2	–	8.4	–	14.4	–	16.0	–	–	–	14.5	–	1.66
Paek et al. (2005)	Household DFW	–	85.3	1.5	20.1	6.0	9.1	11.0	–	–	9.7	21.6	–
Summers et al. (1980)	Institutional	–	24.3	48.4	18.9	57.0	16.9	63.8	–	–	–	–	3.33
	Household	–	21.0	23.0	16.1	24.6	16.9	52.1	–	–	–	–	6.67
	Restaurant	–	24.4	45.9	20.3	37.9	22.9	62.7	–	–	–	–	1.33
Westendorf et al. (1998)	Restaurant	36	22.4	30.1	21.4	20.0	27.2	47.3	–	–	–	–	0.84
Westendorf et al. (1999)	Restaurant, Institutional	63	27.0	19.3	20.8	27.5	26.3	30.4	–	–	–	–	1.44

Abbreviations:
DM: dry matter.
CP: crude protein.
EE: ether extract lipids.
NFE: nitrogen-free extract carbohydrates.
DFW: dried food waste.
MSW: food waste from municipal solid waste.

(44.1%), ether extract lipids 21.5% (33.3%), nitrogen-free extract carbohydrates 38.6% (24.4%), and Ca:P ratio 2.3 (CV 77.8%). Taken together, these findings demonstrate that consumption-stage food waste is generally rich in major nutrients for animals. For instance, the mean crude protein content (19.2%) is nearly double that of maize grain (8–10%). In principle, one ton food waste (dry matter basis) could replace more than the same amount of maize grain to meet the protein requirement of a given animal. In practice, optimal dietary scenarios with different substitution rates can be made using ration formulation programs to simultaneously meet the animal's requirements for multiple nutrients (NRC, 1994, 2012).

A few data gaps remain. First, data properly characterizing nutrient content and variability of food waste are scarce. The relatively large coefficients of variation cited above are based on pooling of different studies. For heterogeneous milieus such as food waste or animal manure, carefully-designed systematic sampling protocols are required in order to obtain representative samples for statistically-rigorous and reliable results (Dou et al., 2001). Although a few studies monitored temporal changes in nutrients from periodically-collected samples (Chen et al., 2015; García et al., 2005; Kim and Kim, 2010), their sampling protocols were insufficient to address the heterogeneous nature of food waste and the variability issue. Furthermore, at centralized treatment facilities where food wastes from numerous sources are mixed, sorted, and treated, nutrient variability in feeds produced would conceivably be lower because of the ‘portfolio’ effect as well as the homogenization impact. But there is limited information to document such impacts. Second, it has been suggested that waste treatment methods may change the nutrient profiles of raw waste materials (e.g. Chen et al., 2015; Murray Martinez et al., 2012). However, there is a lack of cross-comparison studies to quantitatively document potential impacts of food waste treatment on the nutrition profile of pre- and post-treatment samples. Third, the bioavailability of phosphorus in feedstuffs is an important issue in swine and poultry feeding but none of the previous studies examined the issue in relevant samples. Going forward, accurate nutrient characterization, availabilities and variability need to be properly addressed in future studies in order to facilitate the integration of feeds derived from food waste (FDF) into the precision feeding programs of modern-day livestock operations.

2.3. Animal growth performance, meat quality

In various feeding trials, proportions of food waste used in diets (substitution rate) ranged from 10% to 100%. Responses in terms of animal weight gain and/or feed use efficiency varied depending on animal species and physiological stage, length of the feeding trial, and type of food waste and substitution rate. A number of studies reported no difference comparing diets with vs. without substitution (e.g. Chen et al., 2007; Kwak and Kang, 2006; Myer et al., 1999), whereas others have reported decreases in weight gain in chickens (e.g. Chen et al., 2015) and pigs (e.g. Westendorf et al., 1998). Summarizing from multiple studies, zu Ermgassen et al. (2016b) suggested a 13% lower growth rate for pigs with a 50% substitution rate.

Meat quality has been examined through studies comparing diets with vs. without food waste. For example, Westendorf et al. (1998) found that pork from animals fed heat-treated food waste was comparable in flavor and quality to meat from pigs fed a maize-soy diet, judged by a volunteer panel. Sasaki et al. (2007) reported that, through blind tasting, panelists preferred lean meat from pigs fed liquid food waste-based feed compared to a standard diet, for greater tenderness. Using linear mixed models to determine the effects of the inclusion of food waste in pig diets, with the original data derived from a number of studies, zu Ermgassen et al. (2016b) demonstrated that feeding food waste had no effect on 16 of 18 pork quality parameters (e.g. juiciness, dressing percentage, meat color, fat free lean percentage, flavor, overall palatability, etc.). The detected effects of two parameters (monounsaturated fats; marbling) were “weak and did not detrimentally affect pork quality or value”. The researchers concluded that the inclusion of food waste in diets produced pork of similar quality as that from animals fed conventional diets.

2.4. Food waste treatment methods

Pigs were domesticated probably in the ninth millennium BCE (Larson et al., 2007), and fed with food waste or biomass materials inedible to humans, generally without any processing or treatment. However, a highly-transmissible viral swine disease, vesicular exanthema, became widespread in the 1950s in the U.S., which led to state laws mandating cooking (heating) of food waste materials before feeding to pigs (Heitman et al., 1956). Today, heat treatment of food waste prior to animal feeding is a universal requirement, although temperature and duration vary by nation and depending on specific treatment processes.

A number of treatment methods have been reported, which can be grouped into three categories: wet-based, dry-based, and ensiling/fermentation treatment. Wet-based methods typically include a simple heating step to sterilize the raw waste material, rendering it safe for animals. For example, Westendorf et al. (1998) heated food waste and food processing byproducts at 100 °C for 4 h to be used in pig feeding trials. García et al. (2005) sorted food waste out of municipal solid waste; ground (1 mm), homogenized, and heated it to 65–80 °C for 10–60 min; the material as potential feed was then analyzed for nutrients, microbes, and toxins. In general, wet-based feed products are high in moisture content (70–80%) with a relatively short storage life; therefore they need to be utilized near the processing plant within a short time window.

Dry-based treatment combines heating (sterilization) with a drying step to produce feeds with an extended shelf life (80–95% DM) that are easier to handle. For example, Myer et al. (1999) mixed food service waste with soy hulls and wheat flour, pelletized and dried it at 110–120 °C using a fluidized bed dryer. Paek et al. (2005) processed household food waste by rinsing, grinding, dewatering and vacuum dehydration. Kim and Kim (2010) described conversion of residential and restaurant food waste to dry feed by shredding and dewatering, heat-sterilizing, further dewatering, and drying. Chae et al. (2000) used restaurant and household food waste, sieved it to pass 5 mm and dried it in a drum-type dryer at 115 °C. Dry-based treatment is suitable for centralized facilities near urban centers; the feed products can be transported to distant animal operations in rural areas.

Ensiling/fermentation treatment typically consists of the heating-sterilization process followed by the addition of prescribed microbial/yeast agents. The latter utilize readily degradable substrates, stabilizing the material while helping retain the nutrients (Murray Martinez et al., 2012). Procedures and conditions of ensiling/fermentation varied depending on individual studies. For example, Moon et al. (2004) ground household food waste, heated it to 140 °C, then aerobically fermented it for 24 h at 30–40 °C with a probiotic microbial mix containing yeast, lactic acid bacteria and *E. coli*. Chen et al. (2015) described the ensiling processes of a treatment facility where food waste is mixed with wheat and rice bran plus sawdust and beet pulp, a microbial mixture of *Bacillus* sp., yeast and lactic acid bacteria were added, then the materials were fermented for 4–10 h at 60–80 °C, and the final product was dried to 91% DM. In another study, Kwak and Kang (2006) aerobically fermented ground restaurant food waste with a microbial culture and poultry litter at 55–60 °C for 4 h, then vacuum-dried it. Ensiling/fermentation treatment helps prolong the storage of the end product. For instance, Murray Martinez et al. (2012) reported that feed produced from cafeteria food waste after fermentation was stable for up to 30 days.

Additional to the various studies, it is worth mentioning a few interesting endeavors in food waste treatment for animal feeding. There were reports dating back to the 1950–60s in the U.S. (Heitman et al., 1956; Kornegay et al., 1965), which involved having trucks

transporting food waste outfitted with a steam generator and piping system, so that the loads of food waste were sterilized (100 °C for 30 min) on the way to swine feeding sites. Also, in an unusual application of extrusion technology, Kelley and Walker (1999) took cafeteria food waste, mixed with soy hulls and maize meal, ground and dewatered it. The mixture was forced through a commercial pressurized extruder, which sterilized the substrate through friction with temperature reaching 110–135 °C. It is not clear why those early-day adventures did not lead to sustained (business) practices. Several decades later today, the society is striving to simultaneously address the issues of resource limitation, food security, and environmental pollution. Innovative technologies are needed more than ever to effectively and efficiently convert food waste into animal feeds. Systems-based comprehensive studies will need to examine not only the cost-benefit ratio of the treatment per se but also the broader impacts on socioeconomic and resources and sustainability factors.

3. Resource and environmental implications

3.1. Climate footprint

A number of studies using life cycle analysis (LCA) compared the climate footprint of food waste treatment for animal feeding against other waste management options such as anaerobic digestion, composting, incineration, and landfill. In general, GHG emissions associated with the feed-making processes are comparable to those of composting, anaerobic digestion, or incineration, but substantially less than that of landfills. For example, Kim and Kim (2010) calculated GHG emissions to be 200 kg CO_2-eq per ton of food waste with dry-based treatment, 61 kg CO_2-eq with wet-based treatment, 123 kg CO_2-eq with composting, and 1010 kg CO_2-eq with landfill. (Relevant GHG emissions associated with the production of maize and soybeans would be 612 and 720 kg CO_2-eq per ton of grain, derived from Camargo et al., 2013.) Examining results from multiple LCA studies, zu Ermgassen et al. (2016b) stated that the amounts and range of GHG emissions associated with food waste treatment for animal feeding varied considerably between different studies and were sensitive to local conditions and study assumptions.

There is a shortcoming embedded in previous studies, that is, their system boundaries were set as such to examine the climate footprint of the waste management options at the endpoint only. The system boundary precludes consideration of the cascading effects that would be brought forth with the food-waste-to-animal-feed option. When feed grains are replaced by FDF, there would be corresponding reductions in resources that are linked with the production of the grain, such as energy, fertilizer, irrigation water, land, and other agricultural inputs. Corresponding reductions in environmental burdens, e.g. CO_2, N_2O and NH_3 emissions, are also expected. These 'up-stream' resource and environmental benefits need to be taken into account in future studies through full-fledged lifecycle analyses across the entire food system.

3.2. Other resource and environmental implications

Livestock production is costly in terms of resource consumption. In the United States, for example, the production of meat, eggs, and dairy products requires very nearly half of the total acreage of cropland and the amounts of irrigation water and fertilizer nutrients that were used to produce the entire domestic-consumption food supply (Toth and Dou, 2016). Animal production is also associated with environmental externalities (Steinfeld et al., 2006). For instance, European pork production costs €1.4 to the farmer but €1.9 of damage to the environment (through eutrophication, acidification, land use, and greenhouse gas emissions) per kg of pork produced (Nguyen et al., 2012). The environmental costs stem primarily from the processes of feed grain production (Salemdeeb et al., 2017). Substitution of feed grains with FDF would help reduce "livestock's long shadow". It was estimated that cropland required for European pork production could be reduced by 20%, totaling 1.8 million ha, if food waste is recovered and treated with current technologies for pig feeding (zu Ermgassen et al., 2016b). Another study (Salemdeeb et al., 2017) compared food waste treatment technologies (wet- and dry-based) against composting and anaerobic digestion for potential improvement of 14 environmental and health parameters, e.g. ozone depletion, emissions of carcinogens, toxins, eutrophication, etc. Results indicated that the food-waste-for-animal-feeding options scored most favorably with 12 (dry-based) or 13 (wet-based) of the 14 parameters, primarily because of feed grain substitution.

Other resources and environmental benefits associated with FDF replacing feed grains can be substantial. For example, the production of 1 t maize grain requires 110–140 m^3 water and 17 kg N fertilizer in the U.S. (Kim et al., 2014; Monsanto, 2015), or 455–476 m^3 water and 29 kg N in the Chinese production system (Wang et al., 2015; Zhang et al., 2014). The water and fertilizer would be 'spared' if the maize were replaced with FDF. Several other resource and environmental parameters are quantifiable as well, such as energy expenditure, nitrate leaching loss, and N_2O (a potent GHG) emissions. Future studies with quantitative assessment of the resource and environmental benefits potentially provided by the ReFeed strategy would help bring new understanding to the scientific community. Such knowledge would also help raise awareness and stimulate debates on policy priorities and sustainable development agendas.

4. Health/safety issues, cases of select countries

Raw food waste without proper treatment can contain disease-causing bacteria and viruses such as those causing foot-and-mouth disease and classic swine fever. As mentioned earlier, current methods of food waste treatment for animal feeding all include a heating step to sterilize the materials, rendering the products safe for feeding. For example, heat treatment at 65 °C for 20 min was adequate to reduce *Salmonella*, *E. coli* and *S. aureus* to below levels specified as safe for animal feed (García et al., 2005). A hydrothermal treatment at 110 °C for 60 min eliminated *S. aureus*, total coliforms, and total aerobic bacteria, although spoilage molds and yeasts survived at low concentrations (Jin et al., 2012). In principle, current health and safety regulations coupled with proper management protocols are adequate to safeguard the practice of feeding FDF to animals. This is backed by solid evidence in numerous studies as well as in South Korea at the national level (discussed in Section 4.3).

Besides microbial safety, García et al. (2005) reported lead (Pb) and cadmium (Cd) in household and restaurant food wastes being close to or slightly exceeding EU limits, and dioxin (2,3,7,8-tetrachlorodibenzo-p-dioxin) and furan levels exceeding those allowed in livestock feeds. Chen et al. (2015) also found Pb and chromium (Cr) exceeding the Chinese Hygienic Standard for Feeds in hydrothermally-treated food waste samples; pesticides in their samples did not exceed the detection limit of the analytical procedures. It is not clear whether the contamination was incidental or widespread, or how representative the samples were for the source material. More complete data, coupling systematic sample collection with risk analysis, would be valuable for making strategic as well as practical decisions for feed safety.

4.1. The situation in the European Union

Proper treatment of food waste and adequate regulatory and management measures are of paramount importance, as the risk of feeding food waste to animals without proper treatment is high. This is demonstrated by the foot and mouth disease outbreak in the UK in 2001 (Mort et al., 2004), costing £8 billion to the UK economy. The outbreak led to swift legislation (in 2001) banning the use of food waste for animal feeding in the UK; the ban was applied to the entire EU in 2002 (EC regulation 1774/2002; zu Ermgassen et al., 2016b). According to

zu Ermgassen et al. (2016b), the ban does not apply to food waste materials that can be demonstrated to pose no risk of contamination with meat, fish, or other animal products, e.g. certain manufacturing byproducts. Consequently, only about 3 Mt manufacturing byproducts are currently recovered for animal feeding in the EU, compared to an estimated 102 Mt food waste generated. Meanwhile, the EU Waste Framework Directive set a target of zero biodegradable waste (including food waste) at landfills by 2025. Progress is slow and highly variable in different regions toward the set goal (zu Ermgassen et al., 2016a). Paradoxically, a survey of UK smallholder farmers indicated that 24% of the respondents reported feeding uncooked household food waste to their pigs (Gillespie et al., 2015 cited by zu Ermgassen et al., 2016b). This raises the critical question: which policy would be of lower risk – the status quo ban or centralized and regulated use of food waste in pig feeding (zu Ermgassen et al., 2016b)?

4.2. The situation in the United States

The Swine Health Protection Act (U.S. Congressional Record, 1980) stipulates that food waste containing animal parts must be heat-treated at 100 °C for 30 min at licensed operations to qualify for swine feeding. Feeding ruminants with food waste that contains mammalian proteins is prohibited (FDA, 2017), due to the concern of transmission of bovine spongiform encephalopathy (commonly known as mad cow disease). States vary widely in laws and regulations regarding food waste feeding to pigs (Broad Leib et al., 2016). National data on consumption-stage food waste fed to production animals are not available; the practice is probably limited to a small number of pig farms. For example, in the state of New Jersey, from the 1960s to 1994, the number of state-licensed swine food waste feeders declined from 250 to 36, and the number of pigs finished on food waste declined from 130,000 to less than 50,000 head (Westendorf et al., 1996). In alignment with the UN Sustainable Development Goals target 12.3, the USDA and U.S. EPA announced the national goal of reducing food waste by 50% by 2030 (U.S. EPA, 2017). How to attain this goal is not clear. A number of states and local municipalities have created programs recently to promote food waste composting and anaerobic digestion. Quantitatively, however, the amount of food waste recycled through composting and anaerobic digestion is very small − less than 2 Mt (Goldstein, 2017; U.S. EPA, 2016) compared to the 47 Mt generated at the consumption stage (ReFED, 2016). It is a long way to attaining the 50% reduction goal. As a national strategy, ReFeed can serve as a game-changer, provided that relevant policies are created with necessary support in concert with stakeholder engagement.

4.3. The case of South Korea

Unlike the outright ban in the EU or the very limited recovery of food waste for animal feeding in the U.S., South Korea provides a working model to demonstrate that ReFeed as a national strategy can be implemented successfully. There, landfilling of food waste was banned in 2005. Nationwide, about 45% of all food waste is treated for animal feeding, another 45% by composting, and the remaining 10% by other alternatives such as anaerobic digestion, vermicomposting, and co-digestion with sewage sludge (Kim et al., 2011). Food waste generated at the consumption stage is collected separately from other solid wastes and taken to central processing locations for conversion into animal feeds. Typically, around 30% of FDF is from food service businesses such as restaurants, with the remainder from households (Kim and Kim, 2010). At dry-based treatment facilities, food waste is shredded after removing non-food items, dewatered, heat-sterilized, then dried to approximately 80% DM (Kim et al., 2011). Dry-based facilities are located near cities where much of the raw food waste originates, and the feed products can be shipped to animal operations at varying distances. Wet-based treatment facilities are often located on-farm so that feeds produced are utilized on-site in a timely fashion (Kim and Kim, 2010; Kim et al., 2011). There are various combinations of public, private, or public-private partnerships regarding facility set-up, food waste collection and transport, and the operation of facilities, as outlined by zu Ermgassen et al. (2016b). Feed safety is upheld by strict regulations, coupled with proper treatment technologies and control measures such as registration, certification, and stringent feed standards. Since the introduction of the relevant law and its implementation, there have been no animal disease outbreaks associated with the use of feeds derived from food waste in South Korea (zu Ermgassen et al., 2016b).

Japan is also reportedly recycling about 40% of the food waste for animal feeding. Its food waste recycling law was introduced in 2001, which was amended in 2007 to make feed-manufacturing the priority in preference to other alternatives such as composting or incineration (Takata et al., 2012). Currently, the nation's trademarked product, EcoFeed, is produced with source materials primarily from food manufacturing byproducts and surplus grocery and wholesale food; inclusion of restaurant and household food wastes is rather minor (Liu et al., 2016).

5. Other issues and concerns

The stereotypical image of 'garbage feeding' or 'swilling' may hinder the wide adoption of FDF by livestock producers. Contemporary treatment technologies can convert food waste materials into feed products that are value-added and refined, e.g. pelleted dry feed materials, bearing little resemblance to the outdated image of garbage or swill. The FDF can be marketed as commodities. Proper framing could help break away from the old label, creating new 'images' for enhanced acceptance. Toward this end, Singapore's campaign and social marketing for its "NEWater" is an example of remarkable success. NEWater is derived from wastewater after treatment with advanced technologies. It supplies up to 40% of the nation's water needs currently, increasing to 55% by 2060 according to the National Water Agency (PUB, 2017).

The logistics of food waste collection, transport and handling may constitute another concern, since consumption-stage food waste is scattered across numerous food services and homes. Those food waste materials, generally high in moisture content and prone to spoilage, require timely collection and proper handling. GIS-based digital mapping, coupled with the application of advanced logistics tools, can help develop optimal scenarios for food waste collection, transport, and handling. Furthermore, valuable lessons can be drawn from the decade-long successful operation of the programs in South Korea. Besides, food waste collection from diffuse sources at the consumption stage would be similar whether it is for feed-making or composting or anaerobic digestion.

Would livestock farmers benefit from integrating FDF into their operations? The answer is a qualified 'yes' by way of reduced feed cost. For example, Cho et al. (2004) showed that integrating FDF into chicken feeding in Korea could lower feed costs by 2–13%, depending on substitution rates (10% vs. 30%) and the growth stage of the birds. Spinelli and Corso (2000) had similar observations with pig feeding. Furthermore, the case report of the Rutgers-Pinter Farm partnership (U.S. EPA, 2009) illustrates a win-win situation. Accordingly, Rutgers University pays the farmer $30 per (U.S.) ton of food waste hauled from the campus dining services to the pig farm for feeding, instead of the $60 landfill fee the university would have to pay otherwise. It is not clear about the transportation and heating costs or feed-cost savings on the farm, but the economics would certainly favor the farmer as well.

Being cost effective for livestock producers to incorporate FDF into feeding does not necessarily mean that recovering food waste and converting it into animal feed would be economically self-sustaining. A life cycle cost analysis (Kim et al., 2011) suggests that all endpoint options for food waste management – feed-making, composting, digestion, incineration, or landfilling – cost several times more than the direct benefits derived from the products (feeds or compost or biogas; Table 2). Nevertheless, feed-making is the least costly compared to all

Table 2
Cost and benefit analysis ($/ton of food waste) of different food waste management options (adapted from Kim et al., 2011).

Endpoint	Cost					Benefit	Cost/Benefit
	Discharge	Collection	Transport	Treatment	Sum	product	
DF	0	60.79	1.35	72.14	134.29	33.41	4.0
WF	0	60.79	2.58	59.31	122.69	47.36	2.6
Composting	0	60.79	2.80	70.06	133.63	27.53	4.9
AD	0	60.79	0.23	63.74	124.74	12.19	10.2
Co-digest	0	60.79	0.18	17.10	78.05	NA	NA
Disposer	176.18	4.26	0.03	0.10	180.56	NA	NA
Incineration	99.59	10.33	2.23	7.69	119.84	23.72	5.1
Landfill	0	60.79	2.29	14.19	77.24	1.91	40.4

Abbreviations: DF: dry-based treatment for animal feeding.
WF: wet-based treatment for animal feeding.
Composting: aerobic biodegradation, end product (compost) used for land application.
AD: anaerobic digestion, biogas produced used for generating electricity and digestate applied to land.
Co-digest: co-digestion with sewage sludge, biogas generated used for heating digesters.
Disposer: food waste discharged through sewer pipe after grinding.
Incineration: food waste is first dried by a garbage dryer then incinerated with municipal solid waste, heat produced used for residential heating.
Landfill: landfill gas captured and converted to electricity.

other options (Table 2). It must be noted that the system boundary of the study (Kim et al., 2011), allowing the examination of the economic outcome at the endpoint only, precludes the consideration of up-stream resource and environmental impacts associated with feed grain substitution, as discussed earlier. Future studies need to employ systems-based approaches to take full account of the cascading effects. Furthermore, comprehensive economic analysis must encompass not only resource and environmental consequences but also broader impacts such as socioeconomic effects (e.g. job creation) along with full-fledged cost analyses, including infrastructure, technological development, opportunity cost and risk analysis. Such in-depth knowledge is essential for making informed decisions and designing policy incentives moving forward.

6. Concluding remarks

Scientific and field-based studies have provided strong evidence that consumption-stage food waste is rich in major nutrients for nourishing livestock animals, and that contemporary treatment technologies can convert food waste materials, high in moisture content and prone to spoilage, into feed products that are easy to handle and safe to use for animal feeding. Such feeds derived from food waste can replace some of the grains in conventional diets, bringing forth a cascading effect upstream in the food system with potential benefits of resource conservation and pollution mitigation.

In many developed economies, food is being wasted at the consumption stage in very large amounts, owing to complex and interrelated socioeconomic, cultural and psychological factors. Food waste prevention as the ultimate goal is attainable only to a limited extent. Currently-promoted options such as composting and anaerobic digestion for enhanced management of food waste, compared to landfill as the default, have little capacity for simultaneously addressing food security and sustainability challenges. Recovering food waste and converting it into animal feed with modern treatment technologies can be a game-changer, providing the opportunity to simultaneously address food security, pollution prevention, waste management, and resource and climate challenges.

Future research needs to address several important issues. First, systematic sample collection and comprehensive nutrient analysis is needed to provide more accurate data on the complete nutrient profile of pre-treatment food waste and, more importantly, post-treatment feed products, regarding the concentration, variability, and bioavailability of key nutrients. Such information is critical for enabling the integration of food-waste-derived feeds into the precision-feeding routine of today's animal production systems. Second, quantitative assessment to link feed grain replacement with resources and environmental benefits in the entire food system is needed, including major resource indices such as land, water, energy, fertilizer and other agricultural inputs, and environmental parameters e.g. soil erosion, nitrogen losses, and GHG emissions. Such information would bring new understanding to the scientific communities, policy makers, and the public and private sectors as well. Furthermore, inputs and feedback from stakeholders, including feed suppliers, livestock producers, food waste emitters, and consumers, are critical for developing effective interventions to support and promote the adoption of food waste recovery for animal feeding. Finally, comprehensive economic analyses need to examine the full spectrum of cost and benefits, including potential broader impacts, of the ReFeed strategy so as to provide the fundamental basis necessary for the development of sound, effective, and path-changing policies.

Acknowledgements

Dr. Charles Ramberg, Jr. commented on an earlier version of the manuscript and contributed to the framing of the scope of this article. Dr. Mi-Hyung Kim provided email consultation. Dr. Zhenling Cui helped with the literature search. This work was supported in part by the University of Pennsylvania through a University Research Foundation grant.

Author declaration

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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